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SCIENTIFIC REPORT

ABSORPTION BY CO BETWEEN 6600 AND 7125 cm-1

(1.4 Micron Region)

Prepared for:

Advanced Research Projects Agency

Washington 25, D.C.

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ABSTRACT

The absorption by $\rm CO_2$ in the 6600 - 7125 cm⁻¹ region (near 1.4 μ) has been studied with a spectrometer having a spectral resolution of about 1 cm⁻¹. Spectra were obtained for 38 samples of $\rm CO_2$ and $\rm CO_2$ + $\rm N_2$ with pressures as high as 15 atmospheres and paths as long as 933 meters. The strengths of the important bands and the half-widths of several lines have been measured. Photographs of the spectra of all the samples as well as a table of transmittance versus wavenumber are included. Also presented is a table of the integrated absorptance ν $\Lambda(\nu) d\nu$ versus ν , with tabulations for 135 different values of ν

 $\int\limits_{V^{'}}A(\nu)d\nu$ versus $\nu,$ with tabulations for 135 different values of ν for the largest samples.

FOREWORD

This is he second of a series of very detailed reports being published on an extensive investigation of the absorption of infrared radiation by CO₂. These reports contain photographs of spectra and extensive tables which should provide most of the information required to interpret spectra of unknown samples, such as planetary atmospheres, or to calculate the transmission through paths which cannot be simulated in the laboratory.

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SECTION 1

INTRODUCTION AND SUMMARY

Most of the absorption by $\rm CO_2$ in the 6600 - 7125 cm⁻¹ region (\sim 1.4-1.5 a) is due to the $00^{\circ}3$ bands of $\rm C^{12}0_{2}^{16}$ and $\rm C^{13}0_{2}^{16}$. A few difference bands and a combination band also absorb a small amount. The absorption in this region is so weak that it plays only a minor role in the heat balance of the atmosphere. But, because of a few rather unique features of the ands, they could be very useful in the interpretation of spectra of the atmospheres of Mars and Venus. The bands of $\rm C^{13}0_{2}^{16}$ are well separated from those of $\rm C^{12}0_{2}^{16}$; thus, it seems likely that the relative abundances of $\rm C^{12}$ and $\rm C^{13}$ isotopes could be determined. The difference bands $\rm C^{13} \leftarrow C^{13}$ are also easily distinguished from the $\rm C^{13} \leftarrow C^{13}$ and because of the strong temperature dependence of the strength of the difference band, quite a lot could also be learned about the temperature of a planetary atmosphere.

On the high wavenumber side of the very sharp head of the $00^{\circ}3$ band, is a region which is free of absorption lines, but there is considerable absorption due to the wings of lines at lower wavenumbers. Investigation of this region has provided much new information about the shapes of the wings of collision-broadened CO_2 lines. The absorption in this region is very strongly dependent on pressure and on the species of gas present with the CO_2 . Quantitative absorption measurements could, therefore, be useful in analyzing planetary atmospheres.

Before spectra of planetary atmospheres can be interpreted properly, or before the absorption along any given path can be calculated, the strengths, widths and positions of most of the absorption lines must be known accurately. Courtoy has measured the positions of most of the lines with very good precision; but only limited information about strengths and

widths can be obtained from his work. Howard, Burch and Williams have made some quantitative measurements on the absorption in this region, but they covered a limited range of pressures and path lengths and the spectral resolution of their instrument was low.

Kuiper³ has also investigated the absorption by large samples, but his spectra were obtained with only moderate resolution and with sample pressures of several atmospheres.

Because of the !imitations of the previous work, the present investigation was undertaken for the purpose of obtaining data on samples covering wide ranges of pressure and absorber thickness and with sufficient resolution that many of the individual lines could be resolved. A long absorption cell with possible paths as great as 933 meters has enabled us to study samples of very large absorber thickness with sufficiently low pressures that the structure in the spectre is not smoothed out. A shorter absorption cell has also made it possible to study samples at pressures as great as 15 atmospheres in order to measure band strengths accurately. The mean half-width of some of the isolated lines has been measured; the half-widths of many more lines can also be determined by a careful analysis of the data.

The data are presented in great detail for the benefit of workers who require it for their analysis. Spectra of 13 samples covering a wide range of pressures and path lengths have been reproduced and digitized. The reproduced spectra are shown in Section 4 and a table of transmittance $T(\nu)$ versus wavenumber ν is presented in Section 5. Section 6 contains a table of $\int_{\nu}^{\nu} A(\nu) d\nu$, the cumulative integrated absorptance; ν' is the

smallest wavenumber considered for a given sample. Tabulations are made for as many as 135 different values of ν for the largest samples.

SECTION 2

EXPERIMENTAL METHODS

2.1 GAS SAMPLING

Samples of CO₂ and CO₂ + N₂ were contained in two different absorption cells which have been described previously. The longer cell has a base length of approximately 30 meters and was used at as many as 32 passes, giving a total path length of 933 meters. It is approximately 0.9 meters in diameter and can be evacuated to less than 1 micron of Hg or pressurized to as much as 2.5 atmospheres. The shorter cell has a base length of approximately 1 meter and was used at as many as 32 passes. It also can be evacuated or pressurized to as much as 15 atmospheres.

The CO, was taken from the vapor in a dewar which contained both liquid and vapor maintained at a temperature less than about -20°C by a relief valve which never allowed the pressure to exceed 300 psig. We found that there was considerably less water in the sample if it were drawn from the vapor over the liquid rather than drawing it from the liquid and allowing it to evaporate into the cell. It appeared as though most of the water in the CO_2 container was trapped in the liquid CO_2 ; and if the liquid was drawn off the H2O was allowed to enter the absorption cell. Of course the pressure, and thus the temperature, in the dewar dropped considerably and the filling rate decreased as the vapor was drawn off. When the pressure decreased to a point where the filling rate was very low. the valves were closed and the dewar was allowed to warm up before the valves were reopened. Since the large cell was filled to the higher pressures only a few times, we did not feel it was worthwhile to build a heater to submerge in the dewars to decrease the filling time. Approximately two days were required to fill the large cell to 2.5 atmospheres from two dewars of CO₂.

The cell could have been filled in much less time by drawing off the liquid CO_2 rather than the vapor, but the slower technique was chosen because of the drier samples which could be obtained. The amount of $\mathrm{H}_2\mathrm{O}$ in the N_2 was much less than that in the CO_2 ; therefore, it was not necessary to take extreme care to reduce the amount of $\mathrm{H}_2\mathrm{O}$ put into the sample with the N_2 which was drawn off as a liquid into a heat exchanger where it evaporated and entered the cell.

Before introducing a sample into the cell, it was pumped for several hours in order to get rid of most of the $\rm H_2O$ which was adsorbed on the walls. This can be very important, depending on the previous sample in the cell. Even after using this much care, the absorption by traces of $\rm H_2O$ in the sample was bothersome in some regions of the spectrum, particularly between 7000 and 7100 cm⁻¹.

 ${\rm CO}_2$ + ${\rm N}_2$ mixtures were mixed in the cell. ${\rm CO}_2$ was introduced to the desired pressure; ${\rm N}_2$ was then added and the mixing was accomplished by fans inside the absorption cells. No attempt was made to change the relative abundances of the different isotopes of C or O in the samples studied. It is probably safe to assume that the natural abundances of these isotopes were present (${\rm C}^{12}$, 98.9%; ${\rm C}^{13}$, 1.1%; ${\rm O}^{16}$, 99.76%; ${\rm O}^{17}$, 0.04%; ${\rm O}^{18}$, 0.20%). Some results discussed in Section 3 indicate that the abundance of ${\rm C}^{13}$ was in fact about 1.1%. No check was made on the isotopes of C.

Sample pressures less than approximately 0.06 atm were measured with a U-tube oil manometer and a U-tube Hg manometer was used for pressures in the range 0.06 < P < 2 atm. All pressures > 2 atm were measured with a bourdon-type gauge. For all except the lowest pressures used, the errors arising from the uncertainty in the pressure measurements are probably negligible.

Since CO₂ varies significantly from a perfect gas at some of the higher pressures used in this inves igation, it was necessary to account for the Van der Waals' forces giving rise to the deviation from the perfect gas. In calculating the absorber thickness u, the following equation was used:

$$u = W p I \frac{273}{\theta} (atm cm)_{STP}. \tag{2-1}$$

- L is the geometrical path length in centimeters,
- p is the partial pressure of CO2 in atmospheres,
- 9 is the sample temperature in Jegrees Kelvin.
 273/9 accounts for the difference in density
 between room temperature and standard temperature, and
- W is a correction term which accounts for the Van des Waals' forces and is given adequately for the pressures used in this investigation by

$$W = 1.00 + 0.0047 p. (2-2)$$

Except for a few samples at 431°K, all measurements were made with the samples at room temperature, approximately 296°K.

In order to relate the pressure of a sample to the half-width of the absorption lines, it is necessary to account for the different broadening abilities of $\rm CO_2$ and $\rm N_2$ when dealing with mixtures of these two gases. Burch, Gryvnak and Williams bave used an equivalent pressure $\rm P_e$ given by

$$P_{p} = 1.3 p + (P - p)_{0}$$
 (2-3)

where P is the total pressure. It is noted that the equivalent pressure approaches the total pressure for a very dilute mixture of ${\rm CO_2}$ in ${\rm N_2}$, which is a good approximation to the earth's atmosphere.

Since the simple classical theory predicts that the half-width of a line is proportional to the density of molecules. Equation (2-3) should probably be modified to account for Van der Waals' forces which cause the density to increase faster than the pressure. The adjustment can be made in the following way:

$$P_e = 1.3 \text{ W p} + (P - p).$$
 (2-3)

The factor 1.3 is not valid in all portions of the spectrum. But in a detailed study of the shapes of collision-broadened lines which will be described in a separate report, we have found that 1.3 is satisfactory in regions where most of the absorption is due to lines whose centers are a few tenths of a cm⁻¹ away. Therefore, it can be used near the stronger lines of most of the bands. However, the self-broadening factor should be considerably greater in a region such as that between 7100 cm⁻¹ and the head of the 00°3 band at approximately 6990 cm⁻¹ where the absorption is due to the wings of lines whose centers are several cm⁻¹ away. The difference in the self-broadening factor arises from the fact that the shape of the extreme wings of a self-broadened line is quite different from that of a nitrogen-broadened line. Equation (2-3') probably gives a good equivalent pressure in the spectral region covered by this report, except from 6990 to 7100 cm⁻¹ and from 6797 to 6810 cm⁻¹. These regions will be discussed in the report on collision-broadened lines mentioned above.

2.2 RECORDING AND CALIBRATION OF SPECTRA

The spectrometer is "home made" and is contained in a tank which could be evacuated to essentially eliminate absorption due to atmospheric gases outside of the absorption cell. The spectrometer tank, as well as another tank containing the radiation source and chopper, were connected to the absorption cell by means of flexible bellows so that all of the optical path external to the absorption cell could be evacuated.

The spectrometer is of the Ebert type with the main mirror having a 75 cm focal length. It utilized a small grating having a ruled area 64 x 64 mm with 600 lines/mm and blazed at 1.6 microns. The grating was used in the first order and a Si filter eliminated overlapping orders of shorter wavelength. A PbS cell cooled with liquid nitrogen was used as the detector. It was not necessary to cool the detector below dry ice temperature for operation in this wavelength region, but the dewar was designed to hold the liquid nitrogen for use at longer wavelengths. Cooling by liquid nitrogen was, therefore, more convenient and was used since the signal-to-noise ratio was approximately the same at both temperatures.

Three different resolution schedules were used in recording the spectra: the approximate spectral slitwidths for each schedule at three different wavenumbers are given in Table 2-1.

TABLE 2-1
RESOLUTION SCHEDULES

| ν | Spectral Slitwidth (cm ⁻¹) | | | | |
|---------------------|--|----------|----------|--|--|
| (cm ⁻¹) | Schedule | Schedule | Schedule | | |
| | A | B | C | | |
| 6600 | 0.86 | 1.00 | 1.40 | | |
| 6800 | 0.92 | 1.07 | 1.50 | | |
| 7000 | 0.98 | 1.14 | 1.60 | | |

Resolution Schedule A or B was used in obtaining most of the spectra. However, C was used for spectra of a few samples at several passes of the absorption cell for which the signal was low because of reflection losses. By increasing the slitwidth a better signal-to-noile ratio was obtained. The schedule used for each spectrum is listed in Table 4-1.

CO₂ and H₂O lines whose positions are well known, or could be calculated, were used for the wavenumber calibration of the spectra. The calibration lines are separated by an average of about 10 cm⁻¹, which is sufficiently close that the spectrum could be assumed to be linear between them. All the lines used for calibration are listed in Table 4-2 and their positions are shown on the spectra in Section 4.

Background curves were obtained with the absorption cell evacuated for each number of passes for which sample spectra were obtained. The background curve was different for different numbers of passes since the reflectivity of the mirrors in the multiple-pass optics varies with wavenumber. The appropriate background curve, which represents 100 percent transmittance, was then fitted to each spectrum and traced on it. All the sample spectra extended beyond the region of absorption on both ends of the band so that dependable "tie-points" between a spectrum and its background could be established. The transmittance was determined from the ratio of the deflection of the sample spectrum to that of the background curve at the same wavenumber.

Each spectrum was examined and compared with others as a check for consistency. Small changes were made to account for $\rm H_2O$ absorption. The corrections could be made reasonably accurately by comparing the spectra with those of $\rm H_2O + N_2$ samples at the proper pathlengths and pressures. The corrected spectra were then replotted and are shown in Section 4.

As each spectrum was being replotted, pairs of values related to transmittance and wavenumber were punched on IPM cards which served as input for a computer program used to calculate transmittance and integrated absorptance as a function of wavenumber. The results of these calculations are shown in Sections 5 and 6. The instrument and the technique used in the replotting and digitizing are described in Appendix C of Reference 4.

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SECTION 3

DISCUSSION OF ABSORPTION BANDS

3.1 IDENTIFICATION AND FEATURES OF THE ABSORPTION BANDS

All of the absorption bands of the various isotopes of ${\rm CO}_2$ which might be expected to absorb appreciably in this region are listed in Table 3-1. v_0 is the wavenumber of the center of the band for the species and transition indicated. The positions of several lines of the bands with reference "C" have been determined accurately by Courtoy. The bands marked "K" were observed by Kuiper in the Venus spectrum and compared with laboratory data. Values of v_0 for the bands marked SWP were determined from the energy levels given by Stull, Wyatt and Plass.

Spectra of three quite different samples are shown in Figure 4-1 with the centers of the stronger bands indicated. The P-branch of the 02^23-02^20 , 10^03-10^00 , and 02^03-02^00 bands of 0^12016^0 all overlap and are only partially resolved. The 01^13-01^10 and 00^03^0 bands of $0^12016^00^18^0$ also overlap the same region. (In the notation, the lower energy level is omitted when it is $00^00.$) The R-branches of all five of these bands are completely masked by the much stronger 00^03^0 and $01^13-01^10^0$ bands of 0^1201^0 . Resolution considerably better than that used in this investigation would be required in order to positively identify very many of the lines of the five weak bands.

Although the $10^{\circ}3 \div 02^{\circ}0$ band of $C^{12}0_2^{16}$ should occur in a region which is free of lines of stronger CO_2 bands, we were not able to observe it. Most of the absorption near this band results from the wings of the lines of the $00^{\circ}3$ band. A few H_2O lines occur where one would expect to observe the R-branch; the reasing the smallest detectable CO_2 absorption. An estimated maximum value for the strength was calculated and appears in Table 3-2.

TABLE 3-1 CO₂ BANDS BETWEEN 6600 AND 7100 cm⁻¹

| ν _ο -1 | Transition | Species | Reference* |
|----------------------|-------------------------------------|----------------------|------------|
| 6679.75 | 1112 | $c^{12}0_2^{16}$ | K, SWP |
| 6745.05 | 01130110 | $c^{13}0_2^{16}$ | К, С |
| 6780.14 | 00 ⁰ 3 | $c^{13}o_2^{16}$ | К, С |
| 6884.6 | 01130110 | $c^{12}0^{16}0^{18}$ | SWP |
| 6897.58 | 05 50~3 و 50 | $c^{12}0_2^{16}$ | SWP |
| 6905.72 | 10 ⁰ 3⊷10 ⁰ 0 | $c^{12}0_2^{16}$ | SWP |
| 6907.09 | 02 ⁰ 3⊷02 ⁰ 0 | $c^{12}o_2^{16}$ | SWP |
| 6921.51 | 00 [©] 3 | $c^{12}0^{16}0^{18}$ | SWP |
| 6935.05 | 01 ¹ 3-01 ¹ 0 | $c^{12}0_2^{16}$ | к, с |
| 6972.49 | 00 ³ | $c^{12}o_2^{16}$ | к, с |
| 7008.49 | 10 [°] 302 [°] 0 | $c^{12}0_2^{16}$ | SWP |

K, Observed by Kuiper³
C, Band centers and positions of several lines measured by Courtoy¹
JP. Band content and lines

SWP. Band centers calculated from energy levels given by Stull. Wyatt and Plass 7

Some interesting features of the transmission spectra in Figure 4-1 should be noted. The difference band $01^{1}3 \leftarrow 01^{1}0$ associated with the $00^{0}3$ band of $C^{12}0^{1}6$ is seen to be displaced to lower wavenumbers with its band head near 6950 cm⁻¹. The corresponding two bands for the C^{13} isotope appear between 6700 and 6800 cm⁻¹, the shift resulting from the heavier C isotope.

The 11¹2 band near 6680 cm⁻¹ has a shape quite different from that of the other bands. Its P-branch is very weak while the Q- and R-branches are relatively strong.

The spectrum of sample 22 shows two very sharp changes in transmittance at approximately 6989 cm⁻¹ and 6795 cm⁻¹. These arise from the fact that the lines get progressively closer as J-values increase in the R-branch. At about J=44 they double back, causing several lines to occur very close together with none beyond a certain wavenumber referred to as the band head. The rather strong absorption between 6989 and 7100 cm⁻¹ by samples 7 and 15 is due to the strong lines whose centers occur below the band head.

Comparison of the spectra of samples 7 and 15 shows that increasing the pressure shifts the wavenumber of minimum transmittance near 6795 cm⁻¹. At relatively low pressures, the minimum in transmittance occurs very close to the band head because there are many very closely spaced lines nearby. This is true although the lines which occur a few cm⁻¹ lower (J = 12-30) are considerably stronger; but, of course, they are more widely separated. As the pressure is increased without changing the absorber thickness u, the absorption between the lines increases. (For purposes of discussion we can think of doing this by decreasing the path length.) The openings between the closely spaced lines soon become "filled-in" and the nearby absorption no longer increases with prossure. However, a much higher pressure is required to fill-in the wider openings between the stronger lines. Therefore, the absorption by them continues to increase with pressure and thus increase the absorption by them relative to the weaker lines near the band head, giving rise to a Ehift in the transmittance minimum.

Of course, such a shift could also be observed for the corresponding band of $C^{12}0^{16}_2$ provided the proper combination of sample parameters was chosen.

3.2 BAND STRENGTHS

The strength, or intensity, of an absorption band is given by

$$S_{v} = \int K(v) dv, \qquad (3-1)$$

TABLE 3-2
BAND STRENGTHS

| Species volume of the control of the | · 2 × 10 ⁻⁶ | Entire Band | 296 | 7008.61 | $c^{12}_{02}^{16}$ | 10°3⊷02°0 |
|--|--|-----------------------------|-------------------------------|----------|--------------------------------------|-------------------|
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | $9.5 \pm 0.4 \times 10^{-5}$ | P + Q-Branch Entire Band | | | | |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | $4.0 \pm 0.3 \times 10^{-3}$ | R-Branch | 296 | 6679.75 | c^{12016} | 11 ¹ 2 |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | x 10 ⁻⁵ | Entire Band a b | 296 | 6745.05 | $c^{13}_{2}^{16}$ | 01 1301 10 |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | $22.6 \pm 2 \times 10^{-5}$ $44.8 \pm 2.5 \times 10^{-5}$ | q.b | | | · • | |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | $22.2 \pm 1 \times 10^{-5}$ | R-Branch | 296 | 6780.14 | c^{13016} | 00°3 |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | - | Entire Band ^a | 431 | 6935.05 | $c^{12}0^{16}_{2}$ | 0113-0110 |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | 0.019 + 0.003 | P-Branch Entire Band | | | | |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | 0.020 ± 0.002 | R-Branch | 431 | 6972.49 | $c^{12}0\overline{\overset{1}{1}}$ 6 | 00°3 |
| $\begin{array}{c ccccccccccccccccccccccccccccccccccc$ | 0.0033 | Entire Band ^a | 296 | 6935.05 | $c^{12}_{02}^{16}$ | 0113-0110 |
| Species v_0 Temperature Portion atm v_0 Strength v_0 | 0.0410 + 0.003 | P-Branch Entire Band | | | | |
| $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | 0.0205 ± 0.001 | R-Branch | 296 | 6972.49 | $c^{12}0_2^{16}$ | 00 [°] 3 |
| | Strength -1 cm STP | Portion | Temperature ^O K | ∨o -1 | Species | Band |

 a Calculated by assuming relative strengths of bands given by Equation (3-8).

^bBased on absorber thickness u for mixture with ratural abundances of isotopes (C¹², 98.9%; C¹³, 1.1%; 0¹⁶, 99.76%; 0¹⁷, 0.04%; 9¹⁸, 0.20%). To obtain strengths of C¹³0¹⁶ bands for pure C¹³0¹⁶, multiply tabulated strength by 91.

where the integration is performed over all ν for which there is appreciable absorption. $K(\nu)$ is the absorption coefficient which is related to $T'(\nu)$, the true transmittance that would be observed with intinite resolving power, by

$$T'(v) = \exp \left[-u K(v)\right]$$
, or $u K(v)$ -4n $T'(v)$. (3-2)

Of course, if more than one band contributes to the absorption at a given wavenumber, $K(\nu)$, used in (3-1) must include only the portion due to the band being considered.

The strengths of the bands of interest in this report are essentially independent of pressure over the range of pressures used. However, as the pressure is increased, the widths of the lines increase until at 15 atmospheres they are greater than the spectral slitwidth used by us ($\sim 1 \text{ cm}^{-1}$). When this is the case, the observed transmittance $T(\nu) \cong T'(\nu)$, the true transmittance. Then, by combining (3-1) and (3-2), we obtain

$$S_{V} = -\frac{1}{u} \int \mathbf{A} T(v) dv. \qquad (3-3)$$

Measurements from a few different samples of CO₂ with N₂ added to a total pressure of approximately 15 atmospheres were used in Equation (3-3) to determine the strengths of the more important bands. Where possible, the samples used in any spectral region were chosen so that the absorptance was between 0.1 and 0.7. Under this restriction $\Lambda(\nu)$ was large enough to be measured reliably but not too large for $-\ln T(\nu)$ to be determined accurately. As $\Lambda(\nu) \rightarrow 1$, $T(\nu) \rightarrow 0$ and $-\ln T(\nu)$ gets very large; thus a small error in $T(\nu)$ could produce a large error in $\int \ln T(\nu) d\nu$.

It is also possible, under certain conditions, to determine band strengths from transmission spectra when the lines are much narrower than the spectral slitwidth. If $uK(\nu) < 1$ for all ν , $T'(\nu)$ can be expressed by the first two terms of a series formed by expanding (3-2) to get $T'(\nu) = 1 - uK(\nu)$. The true absorptance $A'(\nu) \equiv 1 - T'(\nu)$ is given by

$$A'(v) = u K(v). \tag{3-4}$$

It has been shown 2 that, under the usual spectroscopic conditions,

$$\int A(v) dv = \int A'(v) dv, \qquad (3-5)$$

where $A(\nu)$ and $A'(\nu)$ are the observed and true absorptances, respectively. In order for Equation (3-5) to be valid, the integration must be carried out over the region containing essentially all the absorption.

Thus, we see that if u(x) < 1, the band strength can be obtained from a measu. The quantity A(y) by

$$S_{V} = \int K(v)dv = \frac{1}{u} \int A(v)dv. \qquad (3-6)$$

The absorptance is said to be in the linear region when the conditions exist for the validity of Equation (3-6).

The major disadvantage with working in the linear region is that the absorptance is small and large errors can arise from noise in the spectrum and from slight misplacement of the background curve. The advantages are that the measurements can be made with low resolution and that the pressures need not be as high as when using larger values of $A(\nu)$ [smaller $T(\nu)$] in Equation (3-4).

Plass has calculated the maximum values of A(v) which can be used in Equation (3-6) for various band models having different line strength distributions and different ratios of line width to line spacing. He has also calculated the percentage error introduced under conditions for which the linear relationship is not quite valid. Therefore, if we have some knowledge of the widths and spacing of the lines, we can use Plass' results to determine a correction factor for a band strength calculated by the use of (3-6). This technique is frequently quite helpful when dealing with CO_2 which has reasonably regular line spacing.

For $\Sigma \leftarrow \Sigma$ fundamental or overtone bands such as $C^{>0}_{\circ}$ 3, the strength S_m of a given line within a band is related to the strength S_v of the entire band by

$$S_{m} = S_{v} \quad |m| \exp \left[-\frac{B'' m(m-1)}{k\theta}\right] / Q_{r}. \tag{3-7}$$

m=J-1 for the R-branch and -J for the P-branch. B" is the rotational constant of the lower state; k is Boltzmann's constant, and θ is the temperature. Q_r is the rotational partition function. Equation (3-7) is not valid for a $\mathbb{R}+\Sigma$ band such as $11^{1}2$.

The results of the band strength measurements are summarized in Table 3-2. Since u is expressed in atm cm_{STP} according to Equation (2-1), values of band strengths are in atm⁻¹ cm^{-1}_{STP} cm^{-1} . The STP refers to the absorber thickness but not to the temperature at which the measurements are made.

The P-branches of the $00^{\circ}3$ bands of both $0^{\circ}130_{2}^{\circ}16$ and $0^{\circ}120_{2}^{\circ}16$ are overlapped by the P- and R-branches of the difference bands. Therefore, any measurement in the region of overlapping necessarily includes the contributions of all these bands. In order to calculate the different contributions, it was assumed that the relative strengths of the bands are given by $0^{\circ}160$

$$\frac{s_{v}(01^{1}3-01^{1}0)}{s_{v}(00^{0}3)} = 2 \exp(-hc 667.4/k\theta), \qquad (3-8)$$

 θ is the absolute temperature; 667.4 cm⁻¹ is the difference between the energy levels 01^{10} and 00^{00} ; and h, c, and k represent the usual physical constants. The factor 2 arises from the double degeneracy of the 01^{10} state. By substituting the proper values into Equation (3-8), we obtain 0.078 for 296°K, and 0.215 for 431°K, the two temperatures at which measurements were made.

The strengths of the R-branches of the $00^{\circ}3$ bands were measured directly since they are relatively free of lines from other bands. The P-branches of the $00^{\circ}3$ bands were determined by subtracting the calculated strengths of the $01^{\circ}3 \leftarrow 01^{\circ}0$ band from the combined strengths. It is noted that the strengths of the P- and R-branches are very nearly equal. A summation of the strengths of all the lines given by Equation (3-7) indicates that the R-branch should contribute approximately 52% and the P-branch 48%. The deviation of our measurements from this ratio is less than the uncertainty.

A comparison of the changes in transmittance at the band heads near 6990 and 6950 cm⁻¹ indicates that Equation (3-8) is at least valid to within 15 or 20%. At 296°K the change in the envelope near 6950 cm⁻¹ for a sample having absorber thickness u_1 and equivalent pressure P_e is approximately the same as that near 6990 cm⁻¹ for a sample with the same P_e and u_2 = 0.078 u_1 . There are no two samples which differ in u by exactly a factor of 0.078, the theoretical ratio of the strengths of the bands. But, it is possible to estimate the change in transmittance for a given u from smooth curves through points representing different samples.

The strength of the $01^13 \div 01^10$ band of $C^{12}0_2^{16}$ is seen to increase with temperature between $296^{\circ}K$ and $431^{\circ}K$ with part of the increase coming at the expense of the $00^{\circ}3$ band. The combined strengths of these two bands are $0.0443^{-\frac{1}{2}}$ 0.002 at $296^{\circ}K$ and $0.0473^{-\frac{1}{2}}$ 0.004 at $431^{\circ}K$. Because of the uncertainty in the measurements, it is not possible to determine if the increase is significant. At $431^{\circ}K$, the estimated error is larger than at room temperature because of reduced stability in the optics and possible error in temperature measurement which results in a corresponding error in the value of u usec in the calculation.

The strength of the $00^{\circ}3$ band of $C^{12}0_2^{16}$ is approximately 91.5 times that of the $C^{13}0_2^{16}$ band, where the value of u used in the calculation was that of both $C^{13}0_2^{16}$ and $C^{12}0_2^{16}$ in a sample for which the abundance of the isotopes was not intentionally altered. If we assumed that the strength of the band was not altered by changing the C isotope, the relative strengths should be in proportion to their abundances, 98.9/1.1-90.5 Since this ratio is in good agreement with the observed ratio of 91.5, it is probably safe to assume that the isotopes in our samples were present in their natural abundances.

The R-branch of the 11^{12} band is reasonably well isolated from the P-and Q-branches and its strength could be determined separately. But, because of the overlapping of the P- and Q-branches, it would be difficult to measure the individual contributions. The $10^{\circ}3 \leftarrow 02^{\circ}0$ band could not be detected; therefore, it was only possible to set an upper limit on its strength. It is almost certainly not more than $2 \times 10^{\circ}3$, and is probably quite a bit less.

3.3 HALF-WIDTHS OF ABSORPTION LINES

The shape of a collision-broadened CO₂ absorption line within a few cm⁻¹ of its center can usually be represented by the Lorentz line-shape equation 10

$$k(v) = \frac{S_m}{\pi} \frac{\alpha}{(v - v_0)^2 + \alpha^2}$$
 (3-9)

 $k(\nu)$ is the absorption coefficient of the single line; S_m is its strength, ν_0 is the line center, and α is the half-width which is proportional to pressure.

Under the condition that $S_m u/2\pi\alpha \gg 1$, an absorption line is opaque within a few half-widths of its center. The line is then commonly referred to as a strong line.

Ladenberg and Reiche 11 have shown that the integrated absorptance of a strong line with Lorentz shape is given by

$$\int A(v)dv = 2\sqrt{S_m u \alpha} \quad \text{or} \quad \alpha = \frac{\left[\int A(v)dv\right]^2}{4S_m u}, \quad (3-10)$$

where the integration is carried out over all wavenumbers where there is appreciable absorption. If the conditions for a strong line of known strength are satisfied, α can be determined by Equation (3-10) from a spectrum in which the line is resolved. If the conditions are not satisfied, $\int A(\nu) d\nu$ will show a less-than-square root dependence on pressure.

Lines P2 to P20 (J2 - J20 in the P-branch) of the $00^{\circ}3$ band of $0^{\circ}2^{\circ}0^{\circ}2^{\circ}$ occur in a region which is free of lines of other bands. It can be seen from the spectra of a few samples at pressures less than 1 atm, that there is but little overlapping of these lines. The finite slitwidth of the spectrometer causes the spectra to appear as if there is more overlapping than there really is. If we assume that overlapping is negligible, the integrated absorptance $\int A(v) dv$ over the region containing these lines can be treated as the sum of the integrated absorptances

of all the lines. Then by using values of S_m calculated by use of Equation (3-7), we can determine ω by Equation (3-10) from some of our data on samples at relatively long paths and low pressures for which the strong line condition is satisfied.

It is also possible to determine the mean half-width of several adjacent lines from $\int A(\nu) d\nu$ over the interval in which the lines occur. Values of $\int A(\nu) d\nu$ for samples 18, 19, 32 and 34 over the region containing lines P6 to F20 (m = -6 to -20) were used to calculate $\bar{\mathbb{Q}}^0$, a mean half-width of self-broadened CO₂ at a pressure of 1 atm. (The superscript is used with α , p and k(ν) to denote a pressure of 1 atm.) The calculations were made by the use of the following equation which can be derived on the basis of the preceding discussion.

$$\overline{\alpha}^{\circ} = \frac{p^{\circ}}{4 u p} \left[\int A(v) dv / \sum_{m = -6}^{20} (S_m)^{1/2} \right]^2.$$
 (3-11)

Plass' calculated results on the validity of strong-line and non-overlapping approximations were then used to calculate a correction factor for the value determined by Equation (3-11) from each sample. The correction factors depend on the parameters $Su/2\pi\alpha$ and $2\pi\alpha/d$, where d is the line spacing.

After applying the correction factors, which did not exceed a few percent for any of the four samples used, we arrived at $\bar{\alpha}^0 = 0.100$ for the P6 to P20 lines. The four values obtained from the different samples deviated from the mean by less than $\frac{1}{2}$ 3%, but the uncertainty is probably greater than this. At best, the accuracy of the half-widths cannot be better than the values of strengths used in the calculations.

On the basis of Equation (2-3), we can conclude that the mean half-width of these lines broadened to 1 atm with N₂ would be $0.100/1.3 = 0.077 \, \mathrm{cm}^{-1}$.

The P2 and P4 lines were omitted from the calculation since their strengths are so much less than the others that they could not be considered strong lines for the samples used. The lines beyond P20 were not used since they are overlapped by the 01^13-01^10 band, and the R-branch was omitted because of considerable overlapping and less regular spacing. The data could be used to determine half-widths of lines in these regions, but more sophisticated techniques would be required.

In making the calculations, the integrated absorptance was taken over the interval between 6952.2 and 6968.4 cm⁻¹. The first point is midway between P20 and P22 and the latter is midway between P4 and P6. For the samples used, this integral is very nearly the contribution of the

lines whose centers occur within the interval. The contribution of the wings of lines outside the interval is small and is partially cancelled by the contribution of the wings of the lines within the interval which is lost.

The integrated absorptances over small intervals bounded by points midway between adjacent lines were used in Equation (3-10) to calculate the half-widths of each of the lines individually. Because of the narrowness of the intervals measured, one would expect some "scatter" in the values calculated for the different lines. For example, the values of $\bar{\alpha}^{\rm O}$ determined from sample 19 varied between 0.098 and 0.111, and no significant change with J-value could be observed.

Benedict 10 has found that the half-widths of ${\rm CO_2}$ lines in the 15 u region measured by Madden 12 can be fitted by the following empirical equation.

$$\vec{a}_{m}^{0} = 0.050 + 0.12 \exp \left[-0.16 \, |m| \right] + 0.0042 \, |m| \exp \left[-\frac{B'' \, m(m-1)}{k \, \theta} \right].$$
(3-12)

This equation gives 0.119 cm⁻¹ for P6 and 0.093 cm⁻¹ for P20 with the values for the intermediate lines falling between these extremes. A mean value of 0.103 was obtained by inserting half-widths from Equation (3-12) into the following equation

$$\bar{\alpha}^{0} = \left[\frac{\sum s_{m}^{1/2} \alpha_{m}^{1/2}}{\sum s_{m}^{1/2}} \right]^{2}$$
 (3-13)

The summation was made over m = -6 to m = -20 (P6 to P20).

The mean value of 0.103 based on Equations (3-12) and (3-13) is in good agreement with our 0.100; the uncertainty in line strengths alone could easily account for this discrepancy. Spectra obtained with better resolution would be required in order to determine if there is any significant variation in α^0 with J-value.

3.4 ABSORPTION BETWEEN 6990 and 7100 cm⁻¹

It is well known that the absorption coefficient $k(\nu)$ of a single collision-broadened absorption line is proportional to pressure at any point more than a few half-widths from the line center. (For a discussion of collision-broadened lines see references 6, 8 or 13.) Therefore, we would expect the absorption coefficient between about

to be proportional to pressure, since the absorption is due to the sum of wing contributions of several lines. We have demonstrated that this proportional relationship is true, as will be seen below.

For a sample of pure CO₂, where there is self-broadening only, the absorption coefficient is given by

$$K_{\mathbf{s}}(v) = K_{\mathbf{s}}^{\mathbf{o}}(v) \, \mathbf{p/p}^{\mathbf{o}}, \qquad (3-14)$$

where the subscript s refers to self-broadening and the superscript o indicates a pressure of 1 atm.

Since there are no abcorption lines of significance in this region, the transmittance would not change appreciably over one spectral slitwidth; therefore, we can assume that $T(\nu)$ the transmittance observed with a finite slit is very close to the true transmittance $T'(\nu)$. We can therefore, determine $K(\nu)$ from Equation (3-2).

By combining Equations (3-2) and (3-14), we get, for a pure CO_2 sample,

$$K_s^0(v) = -\frac{p^0}{up} \mathcal{L}_n T(v). \tag{3-15}$$

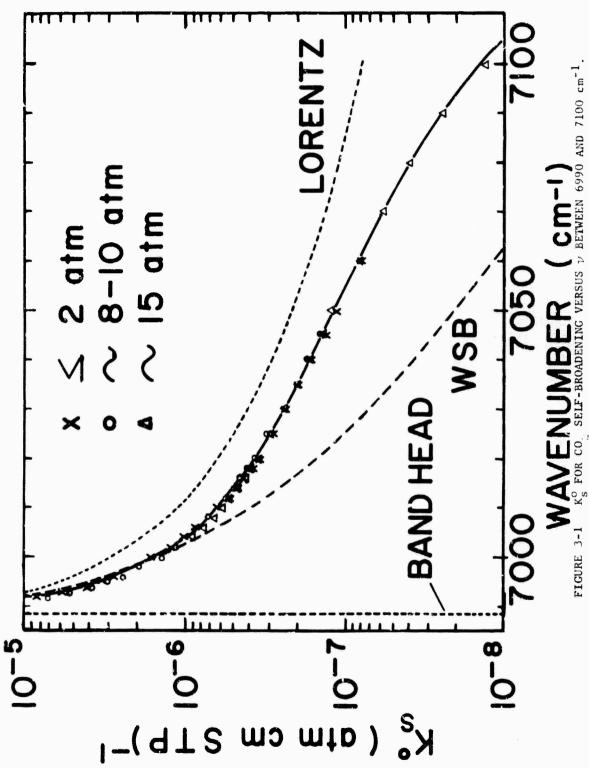
In the case of a mixture of ${\rm CO}_2$ plus a non-absorbing foreign gas with partial pressure ${\rm p}_{\rm f}$, the absorption coefficient is given by the sum of the contributions of the foreign gas and the ${\rm CO}_2$,

$$K(v) = K_s(v) + K_f(v). \tag{3-16}$$

Since K_f is proportional to p_f , Equation (3-15) can be rewritten as

$$-\frac{1}{u} \mathcal{L}_{\eta} T(v) = K_{s}^{o}(v) p/p^{o} + K_{f}^{o}(v) p_{f}/p^{o}.$$
 (3-17)

From curves of transmittance of pure CO₂ samples covering wide ranges of pressure and path length, we have determined $K_s^{\rm O}(\nu)$ for the region from about 6991 to 7100 cm⁻¹. Because of the finite sliwidth of the spectrometer (about 1 cm⁻¹) and possible errors as large as $^{\pm}$ 0.5 cm⁻¹ in calibration, we were not able to get accurate values between 6991 cm⁻¹ and the band head at 6988.5 cm⁻¹. In this narrow interval $K_s^{\rm O}(\nu)$ changes so rapidly that it cannot be considered constant over a slit width, and small errors in calibration also result in large errors in the calculated values of $K_s^{\rm O}(\nu)$.



The various geometrical figures on the solid curve correspond to samples having different total pressures. Ks. the absorption coefficient for self-broadening at pressure p atmospheres, can be found by multiplying Ko from the figure by p. The curve marked "Lorentz" would be obtained if the lines had a Lorentz shape. The curve marked WSB would be obtained if the lines had the shape found by Winters, Silverman and Benedit¹⁰ for

Figure 3-1 shows a plot of $K_s^0(\nu)$ versus ν for the region above the band head. The various geometrical figures correspond to samples having different total pressures. Since they all fall on the same curve, we can conclude that the absorption coefficient is, as we assumed, proportional to pressure.

Also shown in Figure 3-1 are two curves of calculated absorption coefficient. The one marked "Lorentz" was obtained by assuming all the absorption lines had the Lorentz shape while the curve marked "WSB" was obtained by using the line shape found by Winters, Silverman, and Benedict 10 for the lines of the 4.3 u band. In order to perform the calculations we used line strengths given by Equation (3-7) from the value of band strength given in Table 3-2. Half-widths given by Equation (3-12) were used.

It is apparent that the lines of the $00^{\rm o}3$ band are sub-Lorentzian in the wings: that is, they absorb less than a Lorentz shaped line with the same half-width. However, they absorb considerably more than do those in the $4.3~\mu$ band.

After having found $K_s^O(\nu)$ we were able to determine $K^O(\nu)$ by Equation (3-17) for He and N_2 from samples of CO_2 mixed with each of these gases. The results are shown in Figure 3-2 where a portion of the curve for pure CO_2 is included for comparison. Since it is not possible to obtain as large a value of u in a mixture as in a pure gas, and since the broadening abilities of N_2 and He are much less than that of CO_2 , we were only able 12 measure $K^O(\nu)$ for N_2 and He over the region shown.

It is apparent that quite a lot could be learned about the shapes of the wings of collision-broadened CO₂ lines from the measurements beyond the band head. We have carried out quite an extensive set of measurements such as those described above for several different broadening gases in three different spectral regions; near 2400 cm⁻¹, near 3800 cm⁻¹ and the one shown here. From these measurements we have gained considerable new information about line shapes. The results of this investigation will appear in a separate report⁶ within the next few weeks.

Comparison of the spectra cf samples 7 and 15 in Figure 4-1 shows that increasing the pressure has the effect of shifting the $00^{\circ}3$ band of $c^{12}0^{16}_{2}$. In the region above the band head the absorption is a function of the product pu as can be seen by Equation (3-15). Therefore, sample 7 absorbs more than sample 15, although the latter has the larger value of u. But, between 6800 and 6900 cm⁻¹, the absorption is due primarily to lines whose centers are nearby, rather than by the extreme wings of lines. This results in a strong dependence on u and a weak dependence on p, particularly for pressures high enough that the widths of the lines are not small relative to their spacings. Therefore, sample 15 absorbs more in this region than does sample 7. Thus, the apparent shift is due to a difference in the effect of pressure in the different regions of the band, and not to a shift in line centers.

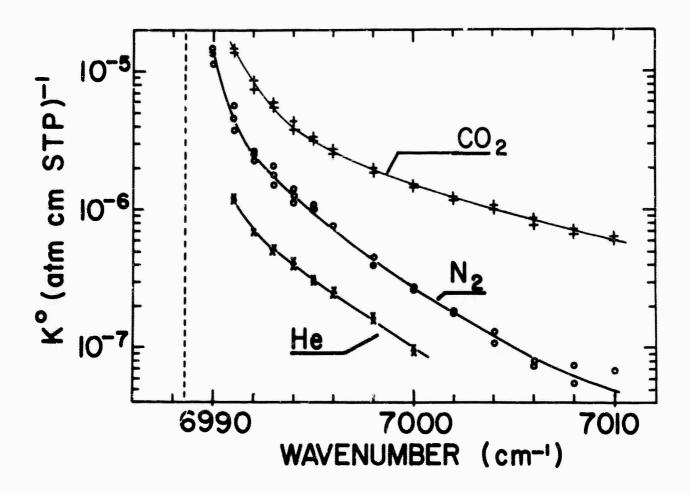


FIGURE 3-2 $\rm K^{\rm o}$ VERSUS ν BETWEEN 6990 AND 7010 cm $^{-1}$ FOR BROADENING BY CO $_2$, N $_2$ AND He.

SECTION 4

SAMPLE PARAMETERS AND TRANSMISSION SPECTRA

4.1 SAMPLE PARAMETERS

The parameters for the 38 samples used in this investigation are summarized in Table 4-1. The following pressures are expressed in both atmospheres and torr (mm Hg):

- p partial pressure of CO₂
- P total pressure due to CO_2 and N_2
- Pe the equivalent pressure which accounts for the difference between self-broadening and foreign broadening by nitrogen. It is given by Pe = 1.3 W p + (P p) where W is a Van der Waals correction given by Equation (2-2).

Also included in the table are the values of path length and absorber thickness given by Equation (2-1). The resolution schedule corresponds to the spectral slitwidth of the spectrometer used to record the spectrum. Each schedule is related to slitwidth according to Table 2-1. Replotted spectra are shown in the pages indicated in the last two columns. All samples were at 296°K, with the exception of 37 and 38 which were at 431°K.

TABLE 4-1
SAMPLE PARAMETERS

| Sam. | p | P | P _e | p | P | Pe |
|------|--------|--------|----------------|--------|--------|--------|
| No. | • | | e | - | | е |
| | | | | | | |
| | torr | torr | torr | atm | atm | atm |
| 1 | 1900 | 1900 | 2500 | 2.50 | 2.50 | 3.29 |
| 2 | 1920 | 1920 | 2520 | 2.53 | 2.53 | 3.32 |
| 3 | 1920 | 1920 | 2520 | 2.53 | 2.53 | 3.32 |
| 4 | 1900 | 1900 | 2500 | 2.50 | 2.50 | 3.29 |
| 5 | 760 | 760 | 992 | 1.00 | 1.00 | 1.31 |
| | | | | | | |
| 6 | 760 | 760 | 992 | 1.00 | 1.00 | 1.31 |
| 7 | 11,100 | 11,100 | 15,500 | 14.6 | 14.6 | 20.3 |
| 8 | 11,100 | 11,100 | 15,500 | 14.6 | 14.6 | 20.3 |
| 9 | 7600 | 7600 | 10,300 | 10.0 | 10.0 | 13.6 |
| 10 | - '00 | 7600 | 10,300 | 10.0 | 10.0 | 13.6 |
| 11 | 7600 | 7600 | 10,300 | 10.0 | 10.0 | 13.6 |
| 12 | 7600 | 7600 | 10,300 | 10.0 | 10.0 | 13.6 |
| 13 | 6080 | 6080 | 8200 | 8.00 | 8.00 | 10.8 |
| 14 | 3020 | 11,100 | 12,100 | 4.00 | 14.6 | 15.9 |
| 15 | 1522 | 1522 | 1995 | 2.00 | 2.00 | 2.62 |
| | | | | | | |
| 16 | 6080 | 11,100 | 13,200 | 8.00 | 14.6 | 17.4 |
| 17 | 175 | 707 | 760 | 0.230 | 0.930 | 1.00 |
| 18 | 175 | 175 | 228 | 0.230 | 0.230 | 0.300 |
| 19 | 88 | 88 | 114 | 0.116 | 0.116 | 0.150 |
| 20 | 29.4 | 29.4 | 38.2 | 0.0387 | 0.0387 | 0.050 |
| 21 | 58.5 | 212 | 230 | 0.0770 | 0.279 | 0.303 |
| 22 | 58.5 | 58.5 | 76.1 | 0.0770 | 0.0770 | 0.100 |
| 23 | 1520 | 1520 | 1990 | 2.00 | 2.00 | 2.62 |
| 24 | 1520 | 1520 | 1990 | 2.00 | 2.00 | 2.62 |
| 25 | 17.8 | 223 | 228 | 0.0234 | 0.293 | 0.300 |
| | _, | | | | | |
| 26 | 17.8 | 72 | 77.2 | 0.0234 | 0.0947 | 0.102 |
| 27 | 17.8 | 17.8 | 23.1 | 0.0234 | 0.0234 | 0.0304 |
| 28 | 8.95 | 8.95 | 11.6 | 0.0118 | 0.0118 | 0.0153 |
| 29 | 760 | 11,100 | 2025 | 1.00 | 14.6 | 2.67 |
| 30 | 506 | 9800 | 9955 | 0.666 | 12.9 | 13.1 |
| 31 | 165 | 9800 | 9850 | 0.217 | 12.9 | 13.0 |
| 32 | 506 | 506 | 660 | 0.666 | 0.666 | 0.868 |
| 33 | 165 | 710 | 760 | 0.217 | 0.934 | 1.00 |
| 34 | 165 | 165 | 215 | 0.217 | 0.217 | 0.283 |
| 35 | 5.8 | 21 | 22.7 | 0.0076 | 0.0276 | 0.0299 |
| 36 | 5.8 | 5.8 | 7.54 | 0.0076 | 0.0076 | 0.0099 |
| *37 | 6080 | 6080 | 8200 | 8.00 | 8.00 | 10.8 |
| *38 | 1535 | 1535 | 2010 | 2.02 | 2.02 | 2.65 |
| | | | a temperature | | | |

Samples 37 and 38 were at a temperature of 431°K; all others at 296°K.

TABLE 4-1 (continued)

| Sam. | L | Ų | Res. | Pages on which | ch spectra appear |
|------|--------|---------|--------|----------------|-------------------|
| No. | Path | ain em | Sch. | 6000- | 6800- |
| | | STP | | 68v0 | 7100 |
| | meters | | | -1 cm | - 1 |
| 1 | 933 | 217,000 | В | 4-7 | 4-12 |
| 2 | 469 | 110,000 | В | 4-7 | |
| 3 | 237 | 55,700 | В | 4-8 | 4-12 |
| 4 | 121 | 28,000 | В | 4-8 | 4-11 |
| 5 | 933 | 86,200 | В | 4-7 | |
| 6 | 237 | 21,900 | В | 4-7 | 4-12 |
| 7 | 32.9 | 47,300 | В | 4-5 | 4-6 |
| 8 | 8.26 | 11,900 | Α | | 4-11 |
| 9 | 32.9 | 31,700 | В | 4-8 | 4-12 |
| 10 | 16.5 | 15, 900 | В | 4-8 | 4-11 |
| 11 | 8.26 | 7,930 | В | | 4-10 |
| 12 | 4.16 | 3,990 | В | | 4-12 |
| 13 | 32.9 | 25,100 | Α | | 4-12 |
| 14 | 32.9 | 12,200 | Α | | 4-10 |
| 15 | 469 | 87,100 | A | 4-6 | 4-6 |
| 16 | 32.9 | 25,100 | Α | 4-7 | |
| 17 | 469 | 9,940 | В | 4-8 | 4-9 |
| 18 | 469 | 9,940 | В | 4-8 | 4-11 |
| 19 | 933 | 9,940 | B C | | 4-12 |
| 20 | 933 | 3,320 | С | | 4-12 |
| 21 | 469 | 3,320 | В | | 4-10 |
| 22 | 469 | 3,320 | В | 4~6 | 4-6 |
| 23 | 32.9 | 6,100 | Α | | 4-10 |
| 24 | 8.26 | 1,530 | Α | | 4-11 |
| 25 | 469 | 1,010 | В | | 4-12 |
| 26 | 469 | 1,010 | В | | 4-10 |
| 27 | 469 | 1,010 | B C | | 4-9 |
| 28 | 933 | 1,010 | С | | 4-10 |
| 29 | 4.16 | 384 | Α | | 4-11 |
| 30 | 16.5 | 1,010 | В | | 4-11 |
| 31 | 16.5 | 330 | В | | , - 11 |
| 32 | 16.5 | 1,010 | В | | 4-10 |
| 33 | 16.5 | 330 | В | | 4-11 |
| 34 | 16.5 | 330 | В | | 4-12 |
| 35 | 469 | 329 | В | | 4-10 |
| 36 | 469 | 329 | В | | 4-12 |
| *37 | 4.16 | 2,170 | Α | | 4-12 |
| *38 | 8.26 | 1,050 | A | | 4-9 |

4.2 CALIBRATION AND TRANSMISSION SPECTRA

Reproductions of the replotted spectra are shown on pages 4-6 to 4-12. Except for Figure 4-1, which includes the entire spectral region covered in this report, the spectra are divided into two intervals and shown separately. The 6600 to $6800~\rm{cm}^{-1}$ interval is shown on pages 4-7 and 4-8, and the $6800~\rm{to}$ $7100~\rm{cm}^{-1}$ interval on pages 4-9 to 4-12. The numbers enclosed in rectangles correspond to the sample numbers given in Table 4-1.

In most cases two or three pectra are included in a single panel of each figure in order to conserve space. The selection of the spectra for any given panel was based on how well they would fit together: no attempt was made to put them in any particular order.

In reducing the data, calibration points were taken at intervals which were short compared to the period of a small periodic error in the screw used to rotate the grating of the spectrometer. Therefore, it can be assumed that the spectra are linear between calibration points. Any error in the determination of the position of a line which might result from this assumption would probably be less than $\frac{1}{2} \cdot (2 \text{ cm}^{-1})$. The positions of known H_2O and CO_2 calibration lines used for calibration are given in Table 4-2. The H_2O lines appeared in the original spectra of some of the large CO_2 samples because of the H_2O which was present as an impurity. The CO_2 lines used for calibration are designated in the upper panels of the spectra on pages 4-7 and 4-9. The numbers on the spectra correspond to the calibration line number.

TABLE 4-2
CALIBRATION TABLE

| Line No. | v cm - 1 | Line No. | v -1 |
|-------------|-------------|-------------|-------------|
| 1 | 7117.5 H* | 16 | 6834.1 Н |
| 2 | 7071.0 н | 17 | 6804.3 H |
| 3 | 7045.5 H | 18 | 6776 |
| 4 | 7021.8 H | 19 | 6773.4 |
| 5 | 6978.7 | 20 | 6765.5 |
| 6 | 6965.7 | 21 | 6756.5 |
| 7 | 6959.9 | 22 | 6749.0 |
| 8 | 6953.4 | 23 | 6740.9 |
| 9 | 6946.2 | 24 | 6732.1 |
| 10 | 6938.4 | 25 | 6722.7 |
| 11 | 6929.9 | 26 | 6709.2 |
| 12 | 6923.9 | 27 | 6688.7 Rl2* |
| 13 | 6917.6 | 28 | 6682.0 R2 |
| 14 | 6907.5 | 29 | 6669.5 Pl2 |
| 15 | 6871.2 H | 30 | 6659.6 P22 |
| | | 31 | 6648.3 P32 |

The wavenumbers designated with an H are those of $\rm H_2C$ lines given by Mohler. Wavenumbers of lines 27-31 were calculated by us from information given by Courtoy on rotational constants. The numbers adjacent to the wavenumbers of these lines refers to the line in $\rm 11^{12}$ band of $\rm C^{12}O_2^{16}$. For example, R12 corresponds to the line in the R-branch which arises from a transition from the J = 12 state. All other lines are from Courtoy.

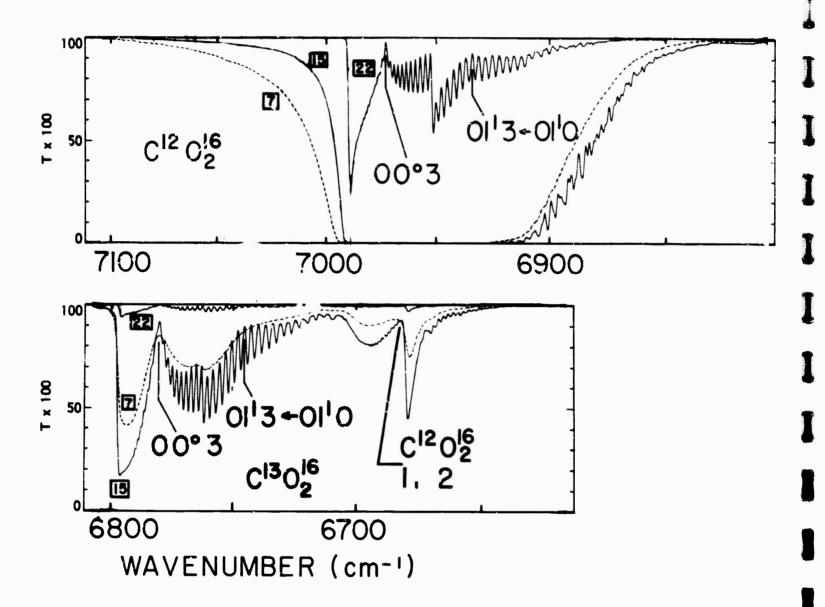
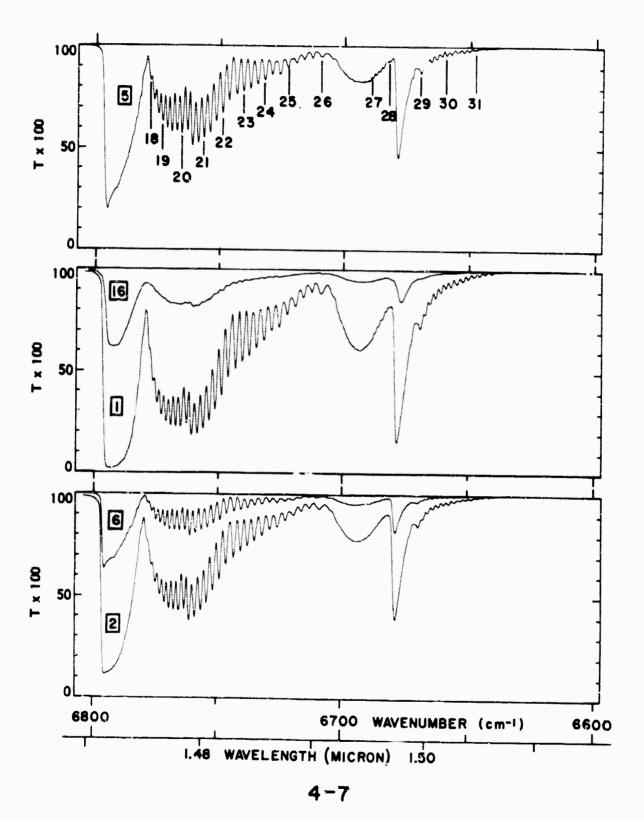
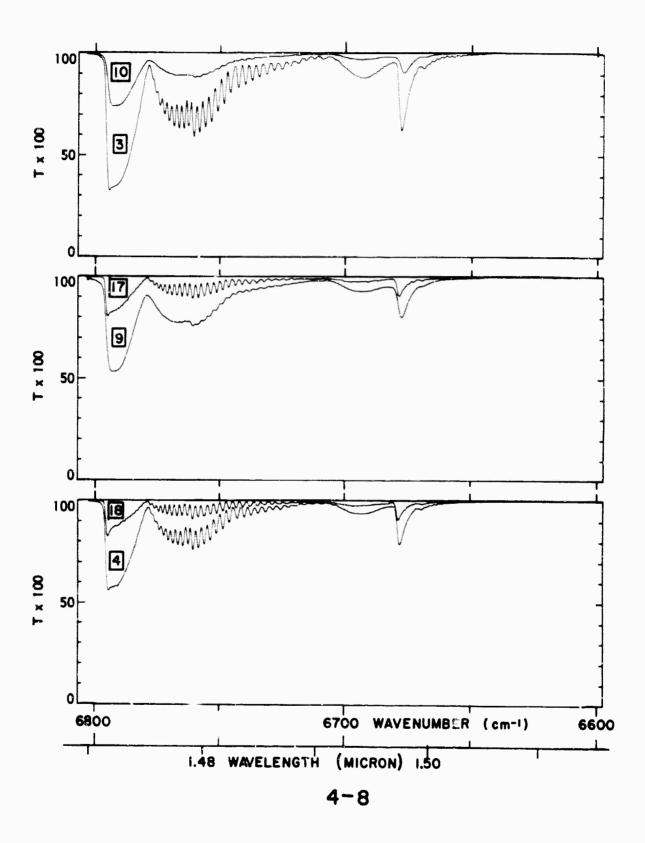
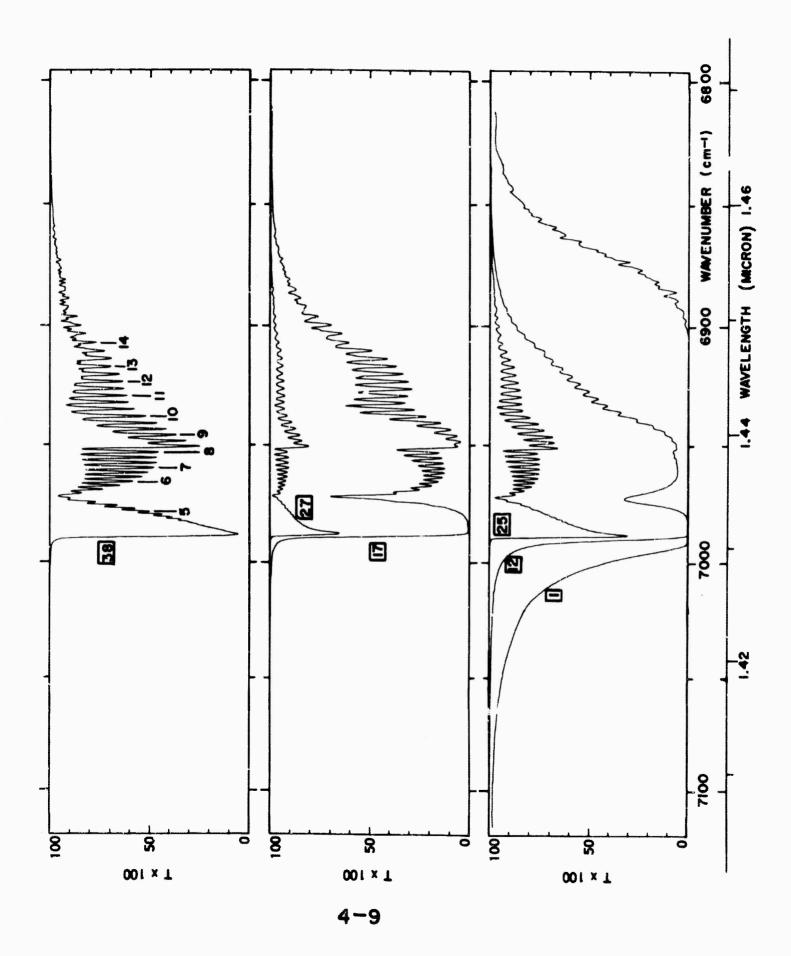


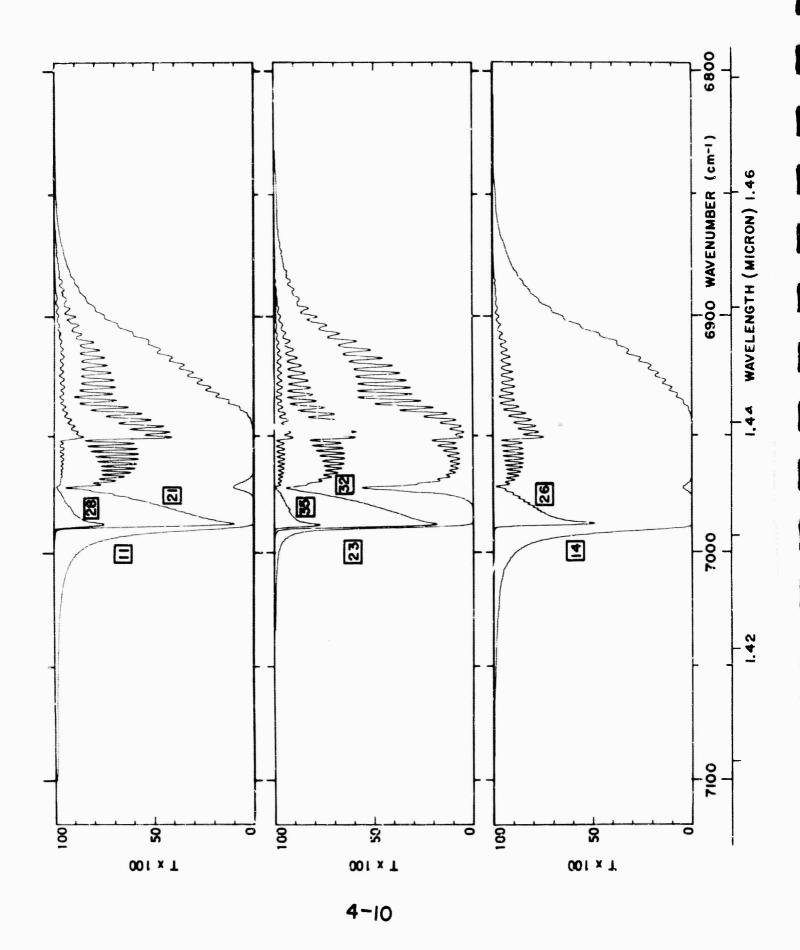
FIGURE 4-1 REPRESENTATIVE SPECTRA OF THE 6600 - 7100 cm⁻¹ REGION.

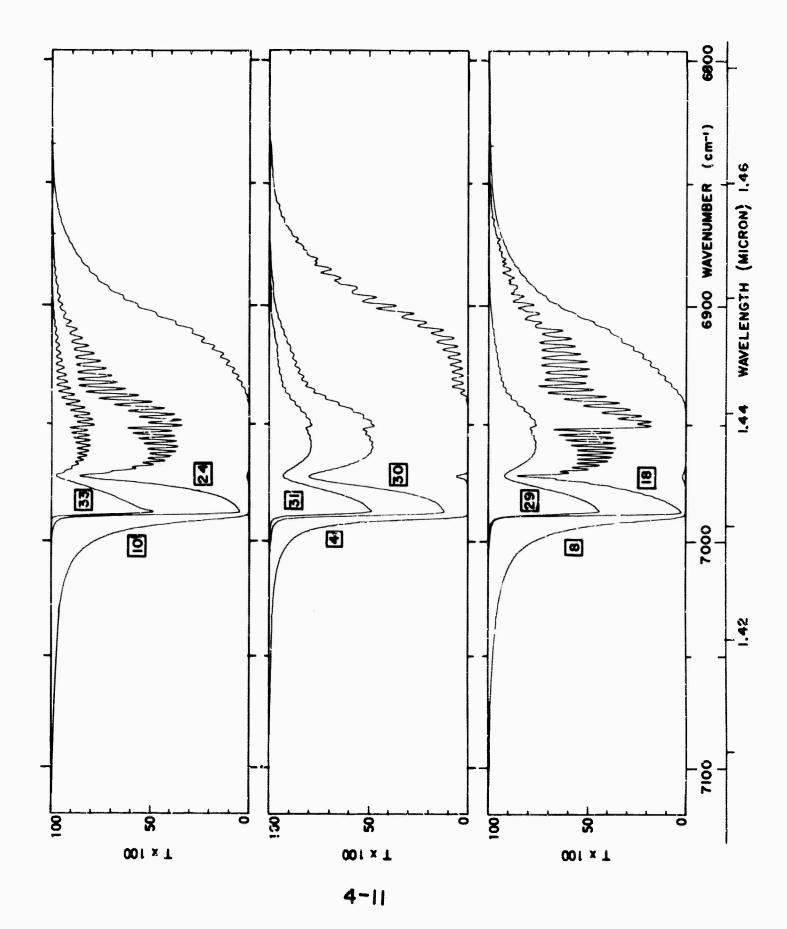
The positions of the centers of the stronger bands are indicated. Other bands in this region are listed in Table 3-1. The numbers enclosed in rectangles are sample numbers. The parameters for all the samples are listed in Table 4-1.

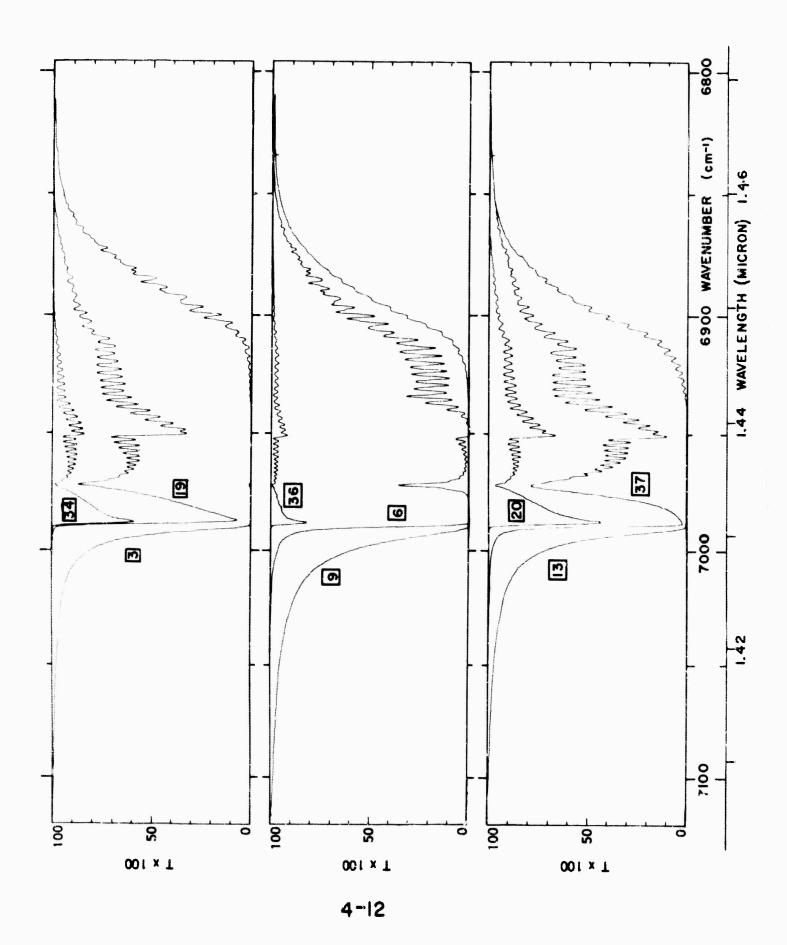












SECTION 5

TABLE OF TRANSMITTANCES

Tables 5-1 and 5-2 consist of values of transmittance, in percent, recorded at intervals of 0.2 cm⁻¹ in the region from 6630 to 6806 cm⁻¹ and from 6813 to 7125 cm⁻¹, respectively. The 0.2 cm⁻¹ interval is sufficiently small that the original spectra could be approximated very closely by plotting the tabulated values and joining the points with straight lines. The first column gives the wavenumber in cm⁻¹, and the second column gives the corresponding wavelength in microns. The tables were made by stripping and photographing portions of the computer output which was obtained from the spectra by the technique described in Section 2.

The CO₂ partial pressure p, the total pressure P due to $\rm CO_2 + N_2$, and the absorber thickness u for each sample are shown at the top of the column corresponding to that sample. These parameters are repeated on a ternate pages for convenience. Each sample is designated by the same number as in Table 4-1 and in the spectra in Section 4. All samples were at 296°K, with the exception of 37 and 38 which were at 431°K.

Values of transmittance are not tabulated over regions of small absorptance (T = 1) for some of the samples. The absorptance between 6806 and 6813 cm⁻¹ is completely negligible except for a few of the largest samples. For these samples it is safe to assume that the absorptance varies linearly between the values tabulated at 6806 and 6813 cm⁻¹. All values for a given wavenumber appear on a single page.

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SECTION 6

TABLES OF INTEGRATED ABSORPTANCE

Values of the integrated absorptance are presented in Tables 6-1 and 6-2 for the regions below and above $6806~\rm cm^{-1}$, respectively. The tables do not cover the entire interval for all the samples. In general, the tables include only the region over which the absorptance is great enough to be measured with reasonable accuracy. The calculations were usually made for groups of from 3 to 5 samples at a time with the limits of integration the same for all the samples in a given group. The lower limit of integration ν' , which is shown at the top of each column, was chosen at a point below which there was little absorption.

The integrated absorptance between any two wavenumbers listed can be found by subtracting the values tabulated at the two points. All of the significant figures are carried in the table in order to avoid losing information when dealing with narrow intervals. The table was formed by stripping and photographing part of the computer output with the proper headings pieced in above each section.

Over a portion of Table 6-2 there are too many values listed at a given wavenumber to include them all on one page. Therefore, they were arranged to appear on successive pages which can be seen simultaneously.

In regions where the structure in the spectra is regular, the integrated absorptance was calculated at wavenumbers midway between the line centers. Therefore, in the case of no overlapping, the difference between

two successive tabulated values is the equivalent width of the absorption line in the interval. In some other regions where the structure was not particularly regular, the integrated absorptance was calculated at wavenumbers corresponding to absorptance minima. In still other regions where there was but little structure or where the absorptance minima would shift as the pressure or absorber thickness was changed, the values were calculated at integral wavenumbers or possibly at integral half-wavenumbers, depending on the amount of information one might expect to obtain from closer readings.

The important parameters for each sample are shown at the top of the column corresponding to that sample. All samples were at $296^{\rm O}{\rm K}$, with the exception of 37 and 38 which were at $431^{\rm O}{\rm K}$.

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| | | | 2.51 ₄ = 10 ⁴ | 0 11 | 0.000.0 | 4 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 | 0.147 | ###################################### | 70000 | 2.068 2.068 2.092 2.157 2.248 | 2.361 2.404 2.475 2.562 | 2.007 2.006 3.014 3.199 | 1.307 1.474 1.474 1.207 | 5.32 5.32 6.1c7 | 7.137 | 7. 0.109 0.709 0.709 0.709 | 10.064 10.063 10.77 | 12.20 12.730 12.013 12.044 12.044 | 12.074 |
| | 2.00 | % # 001 # | 0.71 x 10* | 0798 | 0.028 0.028 0.176 0.178 | 0.4130 | 0.435 1.159 1.341 3.899 | # # # # # # # # # # # # # # # # # # # | 5-927 5-271 5-472 5-472 5-434 | 6 2 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 | 7.800 7.070 8.162 8.402 7.672 | 8.343 6.343 10.152 10.610 | 11.0tq 11.5tq 12.142 12.757 13.573 | 14.487 15.308 17.550 17.555 | 14.309 20.142 20.941 21.749 | 23.00 23.40 23.40 23.40 24.00 24.70 24.70 | | 22.076 33.076 33.076 | 33.476 |
| | 1.00,1 | 1.00 | 1. 50 x 10 | diam. | 2000 | 33277 | PWF=4 0 MF=4 0 M | 00000 | 7.400 7.400 9.575 1.021 | 1.154 1.716 1.266 1.359 | 1.980 | 11.704 | 200 200 200 200 200 200 200 200 200 200 | | ###################################### | 4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 | 4444 4444 4444 4444 4444 4444 | D 4 03 4 44 N 4 4 44 1 4 8 8 8 8 5 4 6 1 8 8 | |
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| | 1.00 1.00 | 1.00 * 100 | 9.62 = 10 | 31-8 31-A | 0.020 | 0.265 0.381 0.467 0.582 0.632 | 0. 74 1.00 1.20 3.59 8.77 | 9.00 9.00 9.10 9.10 9.10 9.10 9.10 9.10 | 11111 | | 7.084 7.213 7.345 7.579 7.630 | 40.745 40.745 40.745 40.745 | 0.941 10.341 10.770 11.525 | 13.603 14.456 15.324 16.005 | 16.70¢ 17.375 10.04¢ 10.25¢ | 14.753 20.130 20.432 20.648 21.224 | 72.04.7 73.500 74.740 75.540 | 20.50 20.547 20.605 20.611 | 24.628 |
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| | , 20°-5 | 2.57 1.09 | 2.80 # 10 | φ <u>ξ</u> ω, , | 0.000 | 2.000 2.000 3.000 5.000 | 7.517 9.073 11.064 13.72 | 24.116 24.116 27.410 30.247 | 33,114 35,496 36,612 41-283 43,931 | ************************************** | \$8.712 60.612 69.017 69.112 | 447.74 | 78.102 79.402 80.800 82.190 | | 14.524. 14.524. 14.524. | 47.47 47.47 40.05 60.05 750 | 44444 44444 44444 |
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| ٠ | 8.00 | 8.00 1.10 2.17 | v.••820 | 0.027 | 1.021 | ### ### ############################## | 10.94 10.94 11.79 11.79 11.79 | 080087 884 884 884 884 884 884 884 884 884 8 | 22.00 24.00 26.00 | 75. 18. 72. 18. 72. 18. 74. 18. | ###################################### | 36-617 40-487 41-214 42-660 42-952 | 45.228 46.003 48.003 90.009 92.95 | 52.636 53.040 33.131 53.162 | - 100 mm m |
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| (cor | 33 | 4.6 4.0 1.0 1.0 | * 10 ² | ı | | | | 1.267 | 1.750 2.004 2.004 2.004 3.222 | 1444 | 9 9 10 4 4 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 | 1400£ 0100£ 0100£ 0100£ | 7.538 6.235 9.643 10.617 | 10.635 10.655 10.665 10.665 | |
| | 32 | 6.66 # 10 ⁻¹ | 4 60.0 1.40.0 | | | | | 44 | 55445 4446 4446 4466 4466 | 0.144 0.149 10.149 10.149 | 11.315 | 8925 UM14 (48f , | 10 - 0 - 10 - 10 - 10 - 10 - 10 - 10 - | 21.94 21.94 21.95 21.95 21.95 | |
| $\left[\int_{-\infty}^{\infty}A(\nu)\mathrm{d}\nu\right]$ | 2.17 | 1.2° 1.2° 1.0° 1.0° | , 10° x | | 0.00 0.00 0.00 0.00 0.00 | 0.035 0.050 0.042 0.116 | 0.233 | 7.4 P. D. G. C. | 2.302 2.302 2.450 3.482 3.482 | 44 N S S S S S S S S S S S S S S S S S S | 6.304 6.610 6.460 7.043 | 7.844 7.450 7.420 8.006 | 9.296 10.169 11.121 17.121 12.593 | चंच्या प्रविक् मा चंच्या के की यो की की यो तो की मा स मा की मा स मा की मा स | 17.155 |
| Α(ν | ος •••• ••• | 1.29 | , 6879 | | 0.00f 0.031 0.055 0.124 | C.222 0.30+ 0.41+ 0.556 0.7+3 | 1.547 | 2.17d 3.17d 5.14d 5.14d 5.14d 5.14d 5.14d | 6.042 7.057 7.259 9.69 | 13.441 | 16.931 | 19.737 27.239 20.643 21.950 21.950 | 25.420 | 30.00 30.00 30.00 30.00 30.00 30.00 30.00 | 90.00 |
| | , 1, 8 1, 86 1, 86 | 1 | * 10² | l | 0.00 0.00 0.00 0.00 | 000000 | 0.272 0.967 0.680 0.680 | 0.921 1.076 1.36.7 1.56.2 1.46.7 | 2000 2000 2000 2000 2000 2000 2000 200 | 66.65 | 7.102 7.462 7.769 7.003 | 2 2 2 C C 2 2 C C 2 C C C 2 C C C C 2 C C C C | 00000000000000000000000000000000000000 | ~ C 37 6 37 6 6 6 7 6 6 7 6 6 8 6 6 | 14.34. |
| 0 | 28 1.18-2 | 1.18-2 x 10-2 | * 10 ⁻³ | | 00000 | :::::: | 000000000000000000000000000000000000000 | 11.11 | 2.533 2.533 2.533 2.533 | 2.006 2.015 3.057 3.144 | 2,442 2,442 3,442 | 0.000 | 4.229 4.229 4.249 1.410 | 9.14 | |
| -9 | 2. #.2 | * 2 m | 7 4.85 1.485 1.485 | | 0000 | 12152 | 0.478 6.825 0.481 1.120 | 50475 | 2000 | 11111 | 5114 | | | 13 | |
| <u>ə</u> | | | F 3' | • | 00000 | 00000 | 0 0 0 | | ****** | | 11111 | ***** | *** | 44 | |
| аp | 2. 76. 2 | # 10 2 2 1 1.01. | 1. | | | 0.524 | | | | | | 25.25 1.45 1.45 1.45 1.55 1.55 1.55 1.55 1.5 | | •• | |
| Table | | | x 10° | , 6 | | 0.574 | 0.764 0.443 1.332 1.552 | 1. 44. 1. 45. 2. 150 2. 350 2. 551 | ****** | 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 | ***** | 6.513 6.772 7.72 7.125 | + G G G G G G G G G G G G G G G G G G G | 100 | |
| Tab | 2, 2, 4, 4, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, | 1.01, | * 10 | | 0.045 0.077 0.028 0.085 0.085 0.085 0.085 0.085 | C.623 O.533 C.244 O.654 O.544 O.674 O.674 | 1.150 0.744 1.424 0.449 1.709 1.149 1.947 1.992 2.248 1.992 | 2,572 2,832 2,832 3,129 2,159 1,419 2,159 1,419 2,192 1,419 | 4.204 4.308 5.408 5.408 5.408 6.408 6.408 6.408 | 6.856 7.242 7.242 7.651 7.661 8.359 8.359 | 8.753 0.022 9.323 9.579 9.519 9.612 | 9.955 16.073 6.624 10.316 6.172 10.594 6.442 | 11.739 12.503 15.403 14.509 14.509 14.509 15.301 | 15,375 9,961 6 | 10 10 10 10 10 10 10 10 10 10 10 10 10 1 |
| Tab | 24 25 2,00 2,34,2 | 2.93_1 9.47_2 x 10_1 x 10_2 1.01_1 1.01, | N 10' N 10' N 10' V* e820 V* e855 V* e853 | | C.196 0.345 0.011 C.141 0.077 0.028 C.193 0.125 0.052 0 C.255 0.254 0.065 C.367 0.562 0.146 | 0.511 C.427 0.226 C.247 C.412 0.539 C.297 C.412 C.547 | 1, 661 1,150 0,744 2,072 2,072 1,424 0,43 1,143 1,043 1,043 1,132 1,132 1,500 | 4.199 2.572 1.742 1.55 5.56 5.507 1.993 1.993 1.50 5.507 1.993 1.50 5.507 1.50 5.507 1.50 5.50 5.50 5.50 5.50 5.50 5.50 5.50 | 7.277 4.204 2.896 1.218 1.228 1.228 1.228 1.228 1.228 1.239 | | 21. 3 6.723 1.799 21. 3 5.022 5.991 21.912 9.321 6.16. 27.912 9.519 6.513 73.241 9.812 6.441 | 23,517 9,905 6,513 6,624 6,524 16,013 6,624 6,172 6,17 | 20.493 11.739 7.244 9 10.263 12.563 12.401 9.16 12.401 9.16 12.401 14.509 9.443 15.243 15.341 0.493 | 15, 194 18, 319 9, 961 9, 194 18, 194 19, 194 19, 194 19, 194 19, 194 19, 194 19, 194 194 194 194 194 194 194 194 194 194 | 54.033 Value 74 (4.037 Property 10.000 Propert |
| Tab | 22 23 24 25 7.70 2.00 24.00 2.34-2 | 7.70 2.00 2.00 2.93 8.42 2.10 8.10 8.10 8.10 8.10 8.10 8.10 8.10 8 | viengo v'ento nio nio nio | | C.196 0.344 0.021 C.141 0.077 0.022 C.193 0.125 0.032 0 C.255 0.254 0.085 C.367 0.562 | 1.974 0.511 C.239 0.226 2.436 7.647 0.533 C.247 3.124 C.A12 0.654 0.539 1.23 1.036 0.479 4.200 1.313 0.674 0.605 | 7.57 7.08 1.661 1.100 0.764 7.367 7.072 1.424 0.443 6.813 7.35 1.773 1.133 17.05 1.503 1.497 1.332 11.544 1.506 2.268 1.552 | 13.47c 4.199 2.572 1.742 1.953 1.5c7 2.5c7 1.953 1.953 1.953 1.953 1.5c7 2.159 1.5c7 2.150 | 27.276 P.115 4.204 2.856 2.421 7.277 4.708 3.218 2.218 2.278 2.278 3.218 2.218 | 25. 19 14.411 6.899 4.727 5.490 8.490 8.490 8.40 | 21. 3 6.723 1.799 21. 3 5.022 5.991 21.912 9.321 6.16. 27.912 9.519 6.513 73.241 9.812 6.441 | \$0.134 23.517 9.955 0.913 \$0.130 23.29 16.073 0.424 \$1.435 24.754 16.316 0.172 \$5.673 25.473 16.394 0.442 \$3.647 26.316 10.099 7.125 | \$4.51; 24.493 11.739 7.844 5-527 30.263 12.503 0.116 6.325 37.116 12.621 0.895 6.2316 44.703 16.859 0.443 6.235 46.243 15.361 C.997 | C4.347 34.394 13.339 9.901 C4.54.3 55.430 19.337 9.601 C4.54.5 54.450 19.377 9.601 C4.664 34.460 24.667 24.667 | |
| Tab | 22 23 24 25 7.70 2.00 24.00 2.34-2 | 2.00 2.00 2.91 9.47-2 1.00 1.95-1 9.47-2 1.00 1.95-1 9.47-2 1.01 1.91 1.01 | viengo v'ento nio nio nio | | (.cr) 6.366 (.396 0.347 0.028 0.318 0.011 0.028 0.028 0.256 (.41 0.017 0.028 0.028 0.256 1.25 0.258 0.258 0.258 0.258 0.258 0.258 | 1.974 0.511 C.239 0.226 2.436 7.647 0.533 C.247 3.124 C.A12 0.654 0.539 1.23 1.036 0.479 4.200 1.313 0.674 0.605 | 2.15 | 4.34.3 13.47c 4.199 2.972 1.742 1.953 4.704 2.032 1.993 1.993 4.704 2.032 1.993 1.993 2.350 1.993 2.350 1.993 2.350 1.993 2.350 1.993 2.350 1.993 2.350 1.993 2.350 1.993 2.350 1.993 2.350 1.993 2.393 1.993 2.393 1.993 2.393 1.993 2.393 1.993 2.393 1.993 2.39 | 27.276 P.115 4.204 2.856 2.421 7.277 4.708 3.218 2.218 2.278 2.278 3.218 2.218 | 10.27 36.19 16.41 6.836 4.727 10.276 12.24 4.950 12.24 12. | 11.401 42.264 °C "93 6.753 1.799 12.400 43.404 21.1. 6.622 5.991 12.632 6.401 2.1.12 9.321 6.10. 12.437 4.401 22.512 9.579 6.513 13.457 4.4323 73.241 9.612 6.441 | 13.5 4.4 15.6 1 | 15-134 56-151; 20-1493 11-739 7-344 10-160 12-503 0-110 11-503 0-110 11-503 11-503 0-110 11-503 11- | 13.227 | #F(2 / |

SECTION 7

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